Forest Sci., Vol. 32, No. 2, 1986, pp. 297–317

FORCAT: A Single Tree Model of Stand Development Following Clearcutting on the Cumberland Plateau

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ABSTRACT. A single tree model, FORCAT, was developed as a forest management tool for the Cumberland Plateau region of East Tennessee. FORET (Shugart and West 1977), a gap model of forest succession in East Tennessee, served as the basic program for the simulation of stand regeneration, competition, tree growth, and mortality. Gap models have been used to simulate successional changes in species composition over periods of up to 1,000 years for many different forest types. Even though the output of gap models has included specific information such as basal area and density, the accuracy of short-term predictions of these variables remains relatively untested for forest management purposes. A test of FORET indicated that the model was not readily adaptable to different sites and management schemes. Therefore, major modifications to the basic program were necessary. Some of the more significant changes included in FORCAT are: (1) beginning the simulation with a mature stand (which was immediately clearcut) rather than bare ground, (2) growth rates based on site quality and local climatic conditions, (3) basing seed availability on species-specific characteristics, and (4) simulation of periodic clearcutting and prescribed burning.

Validation tests showed that FORCAT successfully predicted basal area, numbers of trees, and species composition of 50- to 100-year-old stands. In younger stands, however, the number of seedlings of pioneer species was underestimated. This variance emphasizes the difficulty of projecting regeneration abundance and indicates the need for further model refinement. Nevertheless, FORCAT serves as a bridge from a highly theoretical model of forest succession to a useful forest management tool. Additional inputs controlling seed availability are needed to make FORCAT more broadly applicable to all forest types found on the Cumberland Plateau. FOREST SCI. 32: 297–317.

ADDITIONAL KEY WORDS. FORET, simulation, stand dynamics, land type, prescribed fire, gap model, multiple-use management.

CONFLICTING demands for the use of forest resources suggest the need for multiple use management. An example is found on the Catoosa Wildlife Management Area (CWMA) on the Cumberland Plateau of East Tennessee. The Tennessee Wildlife

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Resources Agency manages this area primarily for high quality wildlife habitat but relies on timber production to carry the cost of management. The choice of management schemes to meet both of these objectives requires not only an understanding of inherent species-site relationships but also the ability to predict the effects of various silvicultural activities on the short- and long-term development of forest stands.

A large portion of the Cumberland Plateau is covered with stands of low-quality hardwoods (McGee 1982). The present management scheme is to clearcut and allow stands to regenerate naturally. Prescribed burns are occasionally conducted in 3- to 5-year-old hardwood clearcuts to maintain browse within the reach of deer for longer periods of time. The immediate benefits of these practices to wildlife are generally evident but their long-term effects on the development of forest stands are not as well understood. Predicting the quantity and composition of regeneration following clearcutting is often difficult. If browsing increases, regeneration characteristics may change, making long-term predictions of stand dynamics even more difficult. To guide management decisions for stands on the CWMA, an easy-to-use model is needed that accurately predicts not only long-term timber production but particularly short-term vegetation changes for wildlife concerns.

Several models of forest stand dynamics are potentially adaptable to the forests of the Cumberland Plateau (see reviews by Munro 1974, Shugart and West 1980, Mitchell 1980, and Trimble and Shriner 1981). The detailed information required for the decision-making process for forest management on the CWMA may be best achieved from a single tree model (Munro 1974). These models simulate the growth of each tree on a given area and are more flexible than models of entire forest stands.

Gap models, a special case of single tree models (Shugart and West 1980), are particularly attractive due to their demonstrated adaptability over a wide range of forest types. These models have been used for the northern hardwood stands of the Hubbard-Brook forest (Botkin and others 1972a, 1972b), loblolly pine (*Pinus taeda* L.) stands in Arkansas (Mielke and others 1978), bottomland and swamp forests of the Mississippi River Delta (Tharp 1978), *Eucalyptus* forests of Australia (Shugart and Noble 1981), and the rain forests of Australia (Shugart and others 1980) and Puerto Rico (Doyle 1981). In addition, gap models are available for forests very similar to those of the CWMA. The original gap model, JABOWA (Botkin and others 1972a, 1972b), was adapted by Shugart and West (1977) to produce FORET, a model of lower-slope Southern Appalachian forests. Other gap models for forests in East Tennessee were developed by Smith and others (1980) and Weinstein (1982).

Gap models generally use simple equations, with parameters that are easily obtained, to approximate the mechanisms that cause a forest to change on a small plot of land (Shugart 1984). Such changes are simulated through the birth, growth, and death of individual trees as controlled by various measures of competition and other environmental factors. Variables used in gap models as limiting factors to tree growth have included shade, stand basal area, soil moisture, and ambient temperature. Gap sizes range from 0.04 to 0.08 ha (Shugart and West 1979), approximating the area opened by the death or removal of an individual canopy tree or forest inventory quadrat (Shugart and West 1980). A more detailed description of gap models is given by Shugart (1984).

Most gap models have been used to simulate forest succession over periods of up to 1,000 years. Emphasis has been on changes in species composition over several seral stages rather than the short-term predictions of stocking, growth, and yield that are needed for many forest management decisions. Even though the output of gap models has included such specific information as basal area and density, the accuracy of short-term predictions of these variables remains relatively untested. Output from simulations as short as 100 years has not been compared to field data collected from managed forests. When compared to local yield tables, the BRIND model (Shugart and Noble 1981) gave reasonable estimates of stocking and yield for *Eucalyptus* forests older than 35 years, but underestimated the stocking of younger stands.

Errors in simulating young stands, such as those of the BRIND model, are common among gap models. Typically, simulations begin with bare ground and with the assumption that there is an equal seed source for all native species. Because of this, convergence of model output with field observations usually does not occur until near the 30th year of simulation. This strategy is certainly adequate for long-term simulations of forest succession, but it may prove to be inadequate for detailed short-term predictions of regeneration characteristics. Shugart and Noble (1981) suggest that with specific management objectives in mind, the performance of gap models can be improved with modifications to simulated seedling establishment and/or the use of species-specific growth equations.

This paper describes the conversion of a succession-oriented gap model to a more practical model intended for use as a management tool. Since gap models are widely accepted for their long-term predictive capabilities, the major emphasis of this study was to improve the short-term predictions of stand dynamics following clearcutting of mature hardwood stands. The resulting model, FORCAT (FORests of the CAToosa), was evaluated primarily for its ability to predict the quantity and composition of regeneration following diameter limit cutting. However, volume, density, and species composition throughout an entire rotation were considered. Problems encountered in model development and suggestions for future improvements are discussed.

VERIFICATION PROCEDURES

The general strategy for developing a model as a tool for forest management on the Catoosa Wildlife Management Area was to first test FORET (Shugart and West 1977) and then use it as the basic program for a new model. Output from FORET was compared to field observations to identify specific problem areas. When problems occurred, FORET was modified, thus creating the new FORCAT model. Improvements that have been made in other FORET-based models (Tharp 1978, Weinstein 1982) were considered for FORCAT. When possible, assumptions and/or techniques used in FORET were altered in FORCAT to make the model more specific to sites on the Cumberland Plateau. Output from FORCAT was compared to field observations to identify new problems. This verification procedure (terminology of Shugart 1984) was repeated until FORCAT output closely resembled field observations. Validation was conducted by a comparison of FORCAT output to a second data set, independent of the one used for verification.

DATA FOR MODEL DEVELOPMENT

Data for the testing of FORET and the verification of FORCAT were collected from 108 permanent sample plots established on the Catoosa Wildlife Management Area in an earlier study (Muncy 1980). This state-owned tract of over 20,000 ha is on the Cumberland Plateau in East Tennessee approximately 16 km north of Crossville. Study plots are on the gently undulating to slightly rolling topography of land type 1 (Smalley 1982). Hartsells and Lonewood fine sandy loams and silt loams are the predominant soils. All are strongly acidic, moderately well drained, of low fertility, and range from 0.5 to 2.3 m in depth to bedrock (Smalley 1982). Site index for upland oaks at age 50 averages 18 m. Vegetation on study areas

TABLE 1. *Preharvest stand characteristics for CWMA study plots.*

Species	Sawtimber (27.9 cm and over)				Pulpwood (7.6 to 27.8 cm)			
	Average trees per ha		Basal area/ha		Average trees per ha		Basal area/ha	
	number	*percent*	m^2	*percent*	*number*	*percent*	m^2	*percent*
Oaks								
Scarlet	33.6	38	4.34	44	45.2	8	0.87	9
Post	25.0	28	2.13	22	115.9	22	3.10	33
Southern red	10.6	12	1.12	11	93.9	17	1.47	16
Black	9.6	11	1.06	11	59.6	11	.99	10
White	1.5	2	.16	2	41.3	8	.62	7
Blackjack	1.5	2	.14	1	4.2	1	.09	1
Chestnut	.2	0.2	.03	0.3	—	—	—	—
Hickories								
Pignut	3.0	3	.39	4	7.9	1	.09	1
Mockernut	.5	0.6	.05	0.5	4.7	1	.07	1
Other overstory hardwoods								
Blackgum	1.0	1	.11	1	4.9	1	.09	1
Red maple	.5	0.6	.07	0.7	5.4	1	.14	1
Understory hardwoods								
Sourwood	.2	0.2	.02	0.2	79.6	15	.80	8
Dogwood	—	—	—	—	16.6	3	.14	1
Pines								
Virginia	2.2	2	.18	2	58.1	11	1.03	11
Total	89.4	100	9.80	100	537.3	100	9.50	100

best fits the post oak (*Quercus stellata* Wangenh.)–blackjack oak (*Q. marilandica* Muenchh.) forest cover type (Type 40, Society of American Foresters 1980) which belongs to the upland oaks type group. Scarlet oak (*Q. coccinea* Muenchh.) and post oak are the dominant species with southern red oak (*Q. falcata* Michx.) and black oak (*Q. velutina* Lam.) as common associates (Table 1). Frequent associates include pignut hickory (*Carya glabra* Mill.), white oak (*Q. alba* L.), blackgum (*Nyssa sylvatica* Marsh.), red maple (*Acer rubrum* L.), Virginia pine (*Pinus virginiana* Mill.), sourwood (*Oxydendrum arboreum* L.), dogwood (*Cornus florida* L.), and sassafras (*Sassafras albidum* Nutt.). Average plot basal area is 19.2 m^2/ha (Muncy 1980).

The quantity and quality of regeneration following clearcutting of these hardwood stands was monitored by Muncy (1980) and Muncy and Buckner (1981). Prior to clearcutting in 1979, 18 permanent plots were established in each of three treatment units on two study areas. Treatments included a diameter limit clearcut (all stems over 7.6 cm dbh harvested), a silvicultural clearcut (all stems over 1.8 m high), and an uncut control. Data used in testing FORET and verification of FORCAT were collected prior to clearcutting (winter 1979) and the end of the first growing season after clearcutting (autumn 1979). Preharvest data included the species, dbh, and total height of each tree found on sample plots. Postharvest data included stem counts of both seedlings and sprouts of all trees in both clearcut and control plots. In study plots that had been clearcut, the number of stump and root sprouts per cut stem was also recorded. Stems which showed evidence of browsing were tallied by species.

Prescribed fire was used in half of each treatment plot prior to the fourth growing

TABLE 2. Input parameters for the FORET model.[a]

Parameter name	Meaning
AAA	Species name
DMAX	Maximum degree-days for species range
DMIN	Minimum degree-days for species range
*b*3	Species-specific growth parameter
*b*2	Species-specific growth parameter
ITOL	Shade tolerance (1 = tolerant, 2 = intolerant)
AGEMX	Maximum age recorded for the species
G	Species-specific growth constant
CURVE	Choice of empirical curve for biomass calculation (1 = deciduous species, 2 = conifers, 3 = yellow-poplar)
SPRTND	Sprouting tendency (0 = no sprouting, 3 = prolific sprouting)
SPRTMN	Minimum dbh at which the species will sprout
SPRTMX	Maximum dbh at which the species will sprout
SWITCH(1)	Does the seed require a litter layer to germinate? (T or F)
SWITCH(2)	Does the seed require mineral soil to germinate? (T or F)
SWITCH(3)	Is the seedling susceptible to hot years? (T or F)
SWITCH(4)	Is the seedling a preferred wildlife food? (T or F)
SWITCH(5)	Is the seed a preferred wildlife food? (T or F)
KTIME	Seed source limitation for old-field successional species

[a] Shugart and West (1977).

season after harvest (late winter 1982). An inventory was conducted in each of the 108 sample plots prior to burning and at the end of the first growing season after burning (autumn 1982 (Waldrop 1983)).

Test of FORET

The FORET model was written in Fortran IV and contains 13 subroutines and functions in addition to the main driving program. The model was designed to simulate stand development on any number of $1/12$ ha plots beginning with bare ground in the first simulated year and continuing for a user-specified number of years. During each simulated year, annual diameter increment for each tree was calculated, regeneration was added to the plot in the form of seedlings and sprouts, and dead trees were removed from the plot. A more detailed description of FORET was given by Shugart and West (1977).

FORET was designed to be adaptable to new forest types by substituting its list of 18 species-specific parameters (Table 2) for those of the species native to a newly modeled area. Parameters for each of 33 species native to the CWMA were either already used in FORET or were obtained from other gap models (Mielke and others 1978, Tharp 1978, Smith and others 1980, Weinstein 1982). FORET was implemented on The University of Tennessee, Knoxville, IBM Series 3071 computer. The model was run to simulate stand dynamics for 100 years and for 100 individual plots.

When model output was compared to CWMA field observations, several problems were recognized. As expected, with model runs beginning with bare ground plots, simulated regeneration had few similarities to regeneration found in CWMA clearcuts. FORET predicted that in year 1, the average plot would have relatively equal numbers of all 33 species and a total of approximately 8,000 stems per ha. In contrast, CWMA clearcuts had 12,000 stems per ha, of which, over 70 percent were of 4 species: sassafras, scarlet oak, blackgum, and red maple (Muncy 1980).

Table 3 compares the percentage of the total basal area as predicted by the

TABLE 3. Comparison of FORET output to CWMA control plot data.

Species	Total stand basal area		
	Predicted at 50 years	Predicted at 100 years	Observed in control plots
	Percent		
Oaks			
Scarlet	0	0	14.7
Post	0	0	31.0
Southern red	0	0	18.5
Black	15.8	28.2	15.9
White	0	0	2.0
Chestnut	1.7	1.0	0
Hickories			
Bitternut	0.9	2.0	0
Pignut	0	0	2.5
Mockernut	0	0	1.3
Other overstory hardwoods			
Blackgum	0	0	1.7
Red maple	13.9	6.5	0.1
White ash	3.0	4.1	0
Black walnut	12.5	11.3	0
Yellow-poplar	30.4	38.5	0
Black cherry	3.8	0.8	0
Understory hardwoods			
Sourwood	0.8	0.1	3.9
Sassafras	10.0	4.2	0
Miscellaneous	3.1	0.2	1.1
Conifers			
Virginia pine	0	0	7.3
Eastern redcedar	4.1	3.1	0

model at years 50 and 100 to data from unharvested CWMA control plots (Waldrop 1983). Since the original condition of control plots may not be the same as simulated plots, this comparison can only be considered a rough verification test. However, central hardwood forests are very stable due to advanced regeneration and sprouting. Species composition 50 years into the future is not likely to be changed by the cultural practices considered in this study. Since the primary objective of this study is to improve the simulation of regeneration characteristics, a rough comparison of long-term species composition, stand basal area, and stand density should be sufficient to identify any gross errors that may cause this type of model to be considered unsuitable for use as a forest management tool.

With the exception of black oak, FORET output had no similarity to CWMA species composition (Table 3). Yellow-poplar (*Liriodendron tulipifera* L.) was the dominant species as simulated by FORET while black oak and black walnut (*Juglans nigra* L.) were common associates. The most common species on control plots were scarlet oak, post oak, southern red oak, and black oak. These results indicate a lack of site-specific considerations by the model for growth and establishment rates of individual species. Dry upland sites such as those of the study area cannot support moisture demanding species such as yellow-poplar and black walnut. These inconsistencies clearly indicated the need for revisions to one or more aspects of the FORET model. Each revision employed will be discussed in the following description of the resulting FORCAT model.

Description of FORCAT

FORCAT was developed through numerous refinements to the FORET gap model (Shugart and West 1977) making it more specific to the managed sites found on the CWMA. The model simulates stand dynamics for 33 species commonly found on the Cumberland Plateau. Simulation begins with a mature stand which is immediately clearcut. After clearcutting, sprouts and seedlings are stochastically added to simulated plots based on the silvical requirements of each species. Diameter and height growth are calculated each year and for each tree as a function of site, species, competition, and environmental stress. Trees are killed stochastically each year based on age, species, and current growth rates. Simulations were limited to periods of 100 years, approximating the upper limit for rotations of low-quality hardwoods. Since FORCAT simulates stand development following clearcutting rather than the death or removal of a single canopy tree, it cannot be considered a gap model. Even though FORCAT retains many of the features of gap models it will be described by the more general term: single tree model. Table 4 summarizes the main operations of each subroutine of FORET and the changes required for FORCAT.

Subroutine PLOTIN.—The PLOTIN subroutine allows the input of stand characteristics so simulation can begin at any age or stage of development. Since simulation in the FORET model began with bare ground, no data were required for PLOTIN. In FORCAT, the dbh, height, and species of all trees on the average preharvest study plot (Table 1) were input to begin simulation with a mature stand.

Simulation of Clearcutting.—A feature of FORCAT not present in gap models is the simulation of diameter-limit clearcutting. During every simulation, the plot begins with a mature stand (as input by PLOTIN) which is immediately clearcut. All trees larger than a user-specified diameter are removed from the plot. The species and dbh of each harvested tree is retained in model arrays to control the simulation of sprouting in later years. In addition to the clearcut in year 1, clearcuts can be specified for any successive year. The user can specify any value for a minimum dbh that is to be harvested.

Subroutine SPROUT.—After any clearcut, the simulated plot is regenerated by the SPROUT and BIRTH subroutines. In FORET, SPROUT added sprouts to the simulated plot after the death of any tree of appropriate size and species. A similar procedure was employed in FORCAT, but with several changes. In FORCAT, it was assumed that the root system dies with the stem and crown of a tree, making sprouting impossible. Therefore, only harvested trees are allowed to sprout. During each simulated year, SPROUT checks to see if any trees were harvested and, if so, a species-specific number of sprouts is added to the plot. In FORET, the number of sprouts per stump was 0, 1, 2, or 3 for nonsprouting and low, medium, and high sprout-producing species, respectively. In FORCAT, this was changed to the mean number of sprouts per stump for each species observed in CWMA study plots. Values range from 0 for pines to 14 for sourwood and red maple. In FORET, species were not allowed to sprout if they were below a specified minimum dbh (SPRTMN) or above a specified maximum dbh (SPRTMX). Since no minimum sprouting diameters were observed on study plots, this requirement was eliminated in FORCAT. Upper sprouting diameters are those reported by Muncy and Buckner (1981) for species on the CWMA.

TABLE 4. Comparisons of the subroutines and functions of the FORET[a] and FORCAT models.

Subroutine or function	FORET	FORCAT
DATA	Read parameters from data cards for 33 lower slope species of East Tennessee.	Renamed INPUT. Read parameters for 33 species of the Cumberland Plateau of East Tennessee.
PLOTIN	Read the numbers, species, and diameters of trees on the plot at the beginning of each model run. All values were set equal to 0 to simulate bare ground.	Read numbers, species, and dbh of each tree on the average preharvest study plot of the CWMA.
INIT	Initialized all arrays not handled by PLOTIN.	Unchanged from FORET.
SEEDPR	Not present in FORET.	Based seed availability on species-specific characteristics.
TEMPE	Determined the number of growing degree-days in each year (included in the main program).	Adapted from Weinstein (1982) to calculate monthly growing degree-days at CWMA plots.
MOIST	Not present in FORET.	Adapted from Weinstein (1982) to estimate the number of drought days in each year based on monthly temperature and precipitation patterns.
RANDOM	Not present in FORET.	Adapted from Tharp (1978) to initiate the selection of a random number.
KILL	Stochastically removed old and/or slow growing trees from the plot.	Used species-specific growth rates to determine the probability of the death of a slow growing tree. Removed trees after diameter limit clearcuts or prescribed fires.
GROW	Calculated yearly growth for each tree as the rate of open-grown trees minus reductions for shading, temperature, and crowding.	A fourth growth limiting factor, moisture stress, and site-specific growth rates were used in the equation for annual growth.
BIRTH	Added up to 700 seedlings to the plot based on species-specific silvical characteristics.	Added up to 1,200 seedlings to the plot based on species- and site-specific characteristics.
SPROUT	Stochastically added from 1 to 3 sprouts to the plot after the death of an overstory tree.	Added from 1 to 14 sprouts (determined by species) to the plot after the harvest of a tree of appropriate size and species.
OUTPUT	Printed the dbh of each tree and other summary statistics.	Unchanged from FORET.
ERR	Printed an error message when the plot had more than 700 trees.	Printed an error message when the plot had more than 1,200 trees.
GGNORD	Drew a random number from a normal distribution.	Unchanged from FORET.
PLOT	Plotted species composition throughout the simulation period.	Unchanged from FORET.
RANDU	Uniform random number generator.	Unchanged from FORET.

[a] Shugart and West (1977).

Subroutine BIRTH.—For each simulated year, the BIRTH subroutine compiles a list of species which are eligible to enter the plot. If a seed source for a species is present, as determined by the SEEDPR subroutine, eligibility for germination can be limited by any of five comparisons of environmental conditions to the silvical requirements of each species. Current environmental conditions are estimated by FORCAT using similar methods as FORET and include (1) the presence of mineral soil, (2) the presence of a litter layer, (3) mean ambient temperature for the growing season, (4) wildlife predation of seeds, and (5) deer browsing preferences. Once a list of species eligible to germinate is compiled, BIRTH stochastically adds seedlings of only these species to the plot.

Two improvements to BIRTH were considered necessary based on CWMA field observations. First, FORET limited seedling establishment of species that are preferred as browse by deer. Although the same theory is used in FORCAT, browsing preferences were determined by field observations (Waldrop and others 1985) rather than data published for other regions of the country.

The second change involved the total number of stems on the simulated plot. In FORET, the number of seedlings and sprouts on a $\frac{1}{12}$ ha plot was limited to 700. This was considered to be a minimum number that would adequately model long-term forest succession. Since Muncy and Buckner (1981) found 1,000 stems per $\frac{1}{12}$ ha plot on the CWMA, BIRTH was altered to allow additional stems to enter the simulated plot.

Subroutine SEEDPR.—The SEEDPR subroutine was not present in FORET and was added to FORCAT to determine the probability of the seed of each species being present on the simulated plot. This probability is based on the following criterion: (i) species present on the plot before harvesting have a high probability of having seed on the plot, and (ii) the probability of seeds entering the plot is smaller for heavy-seeded species than light-seeded species.

The average number of seeds per pound for each species (USDA Forest Service 1974) is input to the model and converted to the mean weight of one seed. SEEDPR then determines the species that has the heaviest seed and assigns a 5 percent probability that seeds of that species will enter the plot. Other species are assigned probability values proportional to their seed weights, relative to the heaviest seed. The probability is doubled for winged seeded species. Final probabilities range from 5 percent for black walnut to nearly 100 percent for sourwood. In the BIRTH subroutine, a probability of 100 percent is assigned to species present on the plot the previous year. A random number from zero to one is selected and compared to the probability value for each species. If the random number is larger, the species are not allowed to germinate that year. Therefore, the species with the heaviest seed can germinate in only 5 percent of the years in which it is not already on the plot.

This method has many limitations since the probability of a particular seed reaching a particular point is determined by many factors other than seed weight. The approach used in this study was, first, to recognize that seed source limitations were required for some species and, second, to reflect at least one factor observed in nature that imposes this limitation, that being the relationship between seed dispersal and seed weight.

Subroutine GROW.—Annual diameter increment for each tree is calculated by subroutine GROW. Using the method of Newnham (1964), growth for each species is assumed to equal that of trees growing under optimal conditions minus some measure(s) of competition and/or environmental stress. This general strategy was used in both FORET and FORCAT. However, the two models differ in the way they estimate growth reductions from competition and stress. In FORET, growth rates were reduced when trees were shaded, grew in dense stands, or were subjected to extreme temperatures. These factors are retained in FORCAT but the method for calculating each of them has been improved. A fourth growth limiting factor, moisture stress, was added to FORCAT. Each growth limiting factor is discussed below.

The basic growth equation used in FORET and FORCAT for trees growing under optimal conditions is

$$\frac{dD}{dt} = \frac{G^*D^*(1 - D^*H/DMAX^*HMAX)}{(274 + 3^*b2^*D - 4^*b3^*D^{**}2)} \tag{1}$$

where

D = present dbh,
H = present tree height,
DMAX = record dbh attained for each species,
HMAX = record height attained for each species,
$b2$ = a constant derived from DMAX,
$b3$ = a constant derived from HMAX, and
G = a constant derived from DMAX and the record age of each species.

Detailed descriptions of the development of this equation were given by Botkin and others (1972b), Shugart and West (1977), and Shugart (1984).

The values for the independent variables in equation (1) were relatively easy to obtain. DMAX and HMAX were listed in either dendrology (Harlow and Harrar 1969) or silvics (Fowells 1965) textbooks and were used to determine the constants $b2$ and $b3$ using the following equations:

$$b2 = 2^*(HMAX - 137)/DMAX \tag{2}$$
$$b3 = (HMAX - 137)/(DMAX^*DMAX). \tag{3}$$

Equations (2) and (3) were developed by Botkin and others (1972b) from Ker and Smith's (1955) height equation,

$$H = 137 + b2^*D - b3(D^{**}2) \tag{4}$$

by choosing $b2$ and $b3$ so that H equals HMAX and dH/dD equals zero when D equals DMAX. The species-specific values for the constant G in equation (1) were determined by different procedures for FORET and FORCAT. In FORET, G values were selected so that dbh would equal ⅔ of the record dbh for each species (DMAX) at ½ of the record age of that species (AGEMX). Values of G for FORCAT were selected by trial and error using different values in equation (1) until calculated growth rates equaled that of the largest tree of each species found on CWMA study plots. This method was suggested by Botkin and others (1972b) and is more site-specific than the one used for FORET. Growth potential is based on the largest tree of each species on the study area rather than the largest ever recorded. In addition, growth is based on rates observed throughout the life of a tree rather than at just one year.

After the growth rate of each tree under optimal conditions is calculated (equation (1)), growth reduction factors are estimated. Each factor gives a result between 0 and 1 which is multiplied by the results of equation (1) to give the final value for annual dbh increment. One of the growth limiting factors is shading. All trees taller than a given tree (equation (4)) are assumed to cast shade on that tree. In FORET, separate growth reduction equations were used for very tolerant and very intolerant species. Weighted averages of the results of these equations are used in FORCAT for the additional categories of tolerant, intermediate, and intolerant species. Species tolerance categories were reported by Daniel and others (1979). The methods and equations used to simulate the effects of shading were described by Botkin and others (1972b) and Shugart and West (1977).

Botkin and others (1972b) assumed that each species had an optimal temperature for photosynthesis and that net photosynthesis decreased as temperatures varied from this optimum. To estimate this second growth limiting factor, Shugart and West (1977) calculated the number of growing degree-days (DEGD) for a site above a base of 5.98 degrees C. The reduction of growth rates due to either warm or cool temperatures was calculated by

$$\mathrm{T(DEGD)} = \frac{4^*(\mathrm{DEGD} - \mathrm{DDMIN})^*(D\mathrm{MAX} - \mathrm{DEGD})}{(\mathrm{DDMAX} - \mathrm{DDMIN})^{**}2} \tag{5}$$

where DDMAX and DDMIN are the maximum and minimum growing degree-days calculated from mean temperatures from the southern and northern extremes of each species' native range. Equation (5) was adapted to FORCAT using species-specific values of *D*MAX and *D*MIN determined by Shugart and West (1977) and Mielke and others (1978).

The third growth limiting factor is horizontal competition due to crowding or root competition. This factor is estimated by the function

$$\mathrm{S(BAR)} = 1 - \mathrm{BAR/SOILQ} \tag{6}$$

where BAR is the biomass of the simulated stand and SOILQ is the maximum biomass recorded for the forests on the CWMA. The value of S(BAR) varies from one in open stands (no growth reduction from competition) to zero in dense stands.

The fourth growth limiting factor, moisture stress, was not used in FORET but was developed by Weinstein (1982) for the FORNUT model. It was adapted to FORCAT with several improvements. Following the theory of Bassett (1964), the reduction of growth rate is proportional to the percentage of drought days in a growing season. The number of drought days in a growing season is determined stochastically by the MOIST subroutine (discussed below). Growth reduction due to drought is calculated in GROW by

$$\mathrm{SMGF}(I) = \frac{GS - [(FJ^*(D3/2)]}{GS} \tag{7}$$

where

SMGF(I) = soil moisture growth factor for species number I,
$D3$ = species drought tolerance category number,
FJ = number of drought days in a year as calculated by MOIST, and
GS = the number of days in the growing season at the CWMA (USDA Soil Conservation Service 1950).

The calculation of growth reduction due to moisture stress in FORCAT (Equation (7)) is somewhat different from that in FORNUT. Weinstein (1982) assumed that the relative drought tolerance of each species ($D3$) was expressed by the average number of drought days occurring at the westernmost extent of the range of each species. Trials of FORCAT using this technique showed some improvement over FORET. However, the need for revisions to the simulation of moisture stress was indicated by simulated stands composed largely of moist-site species such as sugar maple (*Acer saccharum* Marsh.) and black walnut.

A new approach was employed in which the drought tolerance variable (*D*3) was given a value of 1 to 5 for species in the categories of very tolerant, tolerant, intermediate, intolerant, and very intolerant, respectively. Since this type of information has not been published for all 33 species, classification was accomplished by a survey of 18 scientists and field foresters knowledgeable in this area.

Another improvement to the simulation of moisture stress deals with the relative age of simulated trees. In FORNUT (Weinstein 1982), moisture stress was applied equally to trees of all ages. In FORCAT, it is assumed that sprouts and trees over 10 years of age can obtain water through established root systems and are less affected by drought than seedlings. Therefore, a *D*3 value of 1 is assigned to all trees, other than 1- to 10-year-old seedlings, which allows reduced growth rates during droughts but not to the extent that it causes the death of trees with established root systems.

Subroutine TEMPE.—The TEMPE subroutine was not in FORET, but was adapted from Weinstein (1982) for FORCAT. This subroutine calculates the growing degree-days for each simulated year above a base of 5.83 degrees C. The calculation is based on a random selection of mean monthly temperatures from a distribution of temperatures with a mean and standard deviation equal to that observed near Crossville, Tennessee from 1950 through 1979 (United States Department of Commerce 1950–79).

Subroutine MOIST.—The MOIST subroutine was also developed by Weinstein (1982) and adapted to FORCAT to calculate the number of days in each growing season in which soil moisture is too low to support tree growth. The number of dry days is used in GROW to limit diameter growth. Bassett (1964) calculated the amount of available water in the root zone using the Thornthwaite (1948) method, and then converted it to soil water potential in bars for every day of the growing season. This technique is used in MOIST with temperature and precipitation data for Crossville, Tennessee (USDC 1950–79). The number of dry days (*FJ* in equation (7)) is the number of days in the growing season in which water potential is below permanent wilting point (PWP).

Subroutine KILL.—The probability of the death of individual trees in each simulated year is determined as a function of the present age of each tree in both FORET and FORCAT. Only 1 percent of all saplings reach the maximum age recorded for that species (Harlow and Harrar 1969). Slow growing trees are subjected to a second death mechanism. In FORET, trees that grew less than 1 mm in diameter per year, regardless of species, were given a 1 percent chance of surviving 10 years (36.8 percent each year). Increment cores from trees on the CWMA indicated some variability between species in the ability to survive with slow growth. Changes were made in the KILL subroutine of FORCAT to calculate this second death mechanism on a species-specific basis. Minimum allowable diameter growth rates were estimated from increment cores and ranged from 0.5 mm for post oak to 3 mm for yellow-poplar.

Prescribed Fire Simulation.—FORCAT was also revised to simulate the death of all trees in young stands after prescribed burning. An assumption made in the execution of this function was that the fires would be hot enough and that the trees were young enough that all would be top killed. Survival records for stumps of each tree harvested from the plot were updated each year until the time of burning. Stumps with live sprouts before burning were eligible to sprout afterwards. Stumps without sprouts were assumed to be dead.

The assumption that all trees die during a prescribed fire was valid for burns conducted in 3-year-old stands on study plots (Waldrop and others 1985). In older stands, however, larger trees may be better protected from fire and some may survive. Therefore, the prescribed fire function should only be used during the first 10 years after clearcutting. This period is thought to be sufficient to simulate prescribed fires for wildlife management purposes without violating the assumption of 100 percent mortality.

Simulation of Different Land Types.—FORCAT was developed to accommodate future inclusions of the 20 land types found on the midsection of the Cumberland Plateau (Smalley 1982). Each land type represents a different site in terms of topography, forest productivity, and species composition. A separate value is used for the growth constant, *G*, in equation (1) for each species and land type to simulate the variable growth rates of species on different sites. Increment cores were collected to determine *G* values for only one land type (land type 1). Values for the remaining 19 were estimated from site indices for each land type as reported by Smalley (1982) using the method suggested by Botkin and others (1972b). These values were not tested and will probably require adjustment as data become available.

Verification Results

Verification of FORCAT as an accurate simulator of stand dynamics for forests on the Cumberland Plateau was accomplished by comparison of model output to CWMA study plot data. The dbh, height, and species of each tree on the average study plot prior to harvest was input to the PLOTIN subroutine. FORCAT was run to give the average of 100 independent plots, over a 100 year period following a clearcut of all trees over 7.6 cm dbh.

FORCAT showed a considerable improvement over FORET in its ability to predict most regeneration characteristics after clearcutting (Table 5). In both simulated and observed plots, the most abundant species during the first year after clearcutting were those that were present before harvest. All species that were observed in study plots were also present on the simulated plot. Seedlings of moist-site species, such as black walnut and yellow-poplar, were occasionally present on simulated plots but rarely survived due to moisture stress. Heavy-seeded species that were not present before harvest, such as bitternut hickory (*Carya cordiformis* (Wangenh.) K. Koch), rarely invaded the simulated plot. The total number of stems predicted by FORCAT in year 1 was 939 per $\frac{1}{12}$ ha plot as compared to 989 observed in study plots.

Errors were apparent, however, in the prediction of relative species abundance during the first year after clearcutting. Simulated plots had a fairly even mixture of all of the oak species while scarlet oak was dominant on study plots (Table 5). Scarlet oak composed 20 percent of the total number of stems on study plots during year 1 compared to only 4.5 percent on simulated plots. Values lower than field plot observations were also simulated by FORCAT for red maple, blackgum, and sassafras. Grouping species at the generic level, the model simulated the relative abundances among oaks, hickories, and other species for the first year of recovery following clearcutting. While relative abundances are generally quite variable in young, regenerating stands, the model tended to overestimate the presence of oaks and hickories resulting in an underestimation of the number of "other hardwoods." These differences were not considered serious, however, since there were sufficient numbers of trees of all species normally found on the CWMA to give an adequate appraisal of the availability of browse. In addition, these differences are minor relative to the errors observed during the testing of FORET.

As with other FORET-based models, predicted species composition converged toward composition in field study plots as simulations progressed. Species com-

TABLE 5. Comparison of the average CWMA field plot to the average plot simulated by FORCAT.

Species	Total number of stems		Total basal area		
	Simulated year 1	Observed year 1	Simulated year 50	Simulated year 100	Observed controls
	Percent		*Percent*		
Oaks					
Scarlet	4.5	20.0	11.2	24.0	14.7
Post	6.5	2.0	11.5	21.3	31.0
Southern red	8.6	4.0	11.1	1.6	18.5
Black	7.6	8.0	10.3	13.3	15.9
White	5.7	1.0	9.0	4.7	2.0
Blackjack	3.1	.1	8.1	4.4	.9
Chestnut	2.5	.1	4.4	3.2	.1
Group total	38.5	35.2	65.6	72.5	83.1
Hickories					
Pignut	8.0	3.0	7.7	8.3	2.5
Mockernut	3.8	.5	4.6	.8	.1
Group total	11.8	3.5	12.3	9.1	2.6
Other overstory hardwoods					
Red maple	2.3	13.0	2.5	2.4	.1
Blackgum	7.9	16.0	9.0	9.6	1.7
Group total	10.2	29.0	11.5	12.0	1.8
Understory hardwoods					
Sassafras	9.7	24.0	3.4	1.1	.1
Dogwood	9.8	4.0	4.9	1.5	.1
Sourwood	10.6	1.0	.3	.1	.1
Group total	30.1	29.0	8.6	2.7	.3
Pines					
Eastern white	.2	.1	1.5	2.9	.1
Virginia	.1	.4	—	—	7.3
Group total	.3	.5	1.5	2.9	7.4

position for the average of 100 simulated plots over a 100-year period is summarized in Figure 1. The distance between any two curves at any point along the X-axis represents the percentage of the total plot basal area accounted for by that species at that particular stand age. Dominant species on simulated plots were pignut hickory, blackgum, and all of the oaks. Scarlet oak and post oak were the most common species, particularly at stand age 100. Scarlet oak represented 11.2 percent of the total plot basal area at year 50 and 24.0 percent at year 100 (Table 5). Corresponding values for post oak were 11.5 percent at year 50 and 21.3 percent at year 100. Occasional individuals of red maple, mockernut hickory (*Carya tomentosa* Nutt.), and white pine (*Pinus strobus* L.) were observed in the overstory of simulated plots. Major understory species were dogwood, sourwood, and sassafras. These species remained a component of the simulated plots throughout the 100-year period but their relative importance decreased as overstory trees became larger.

Plots simulated by FORCAT had many similarities to observed control plots. With the exception of Virginia pine, all potential overstory species that were

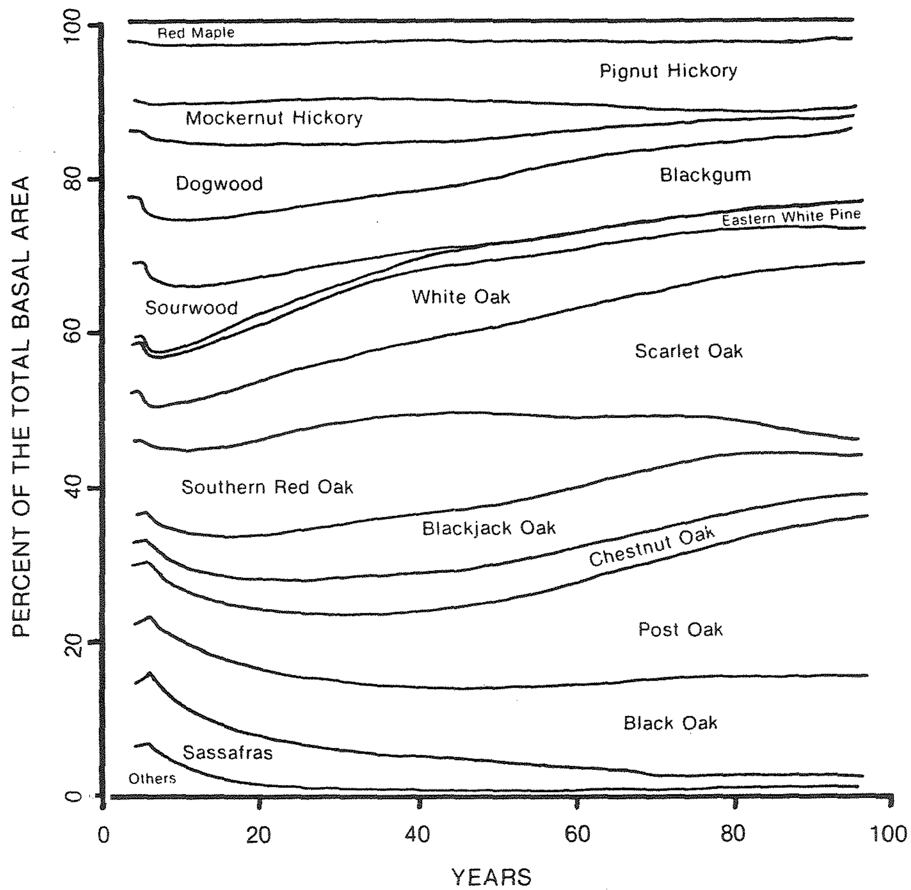

FIGURE 1. Simulated species composition for land type 1. The distance between any two curves at any point along the X-axis represents the percentage of the total plot basal area by that species at that particular stand age.

present on control plots were also present on simulated plots. Moist-site species such as sugar maple, black walnut, and yellow-poplar remained absent from simulated plots. Fields plots were dominated by post oak, southern red oak, scarlet oak, and black oak (Table 5). Each of these species was also a major component in simulated plots at separate times throughout the 100 year simulation. Understory species were also correctly simulated. Dogwood, sourwood, and sassafras were the most common of this group in both simulated and observed plots.

Other similarities between observed and simulated plots included tree number and total plot basal area. At year 100, there was a total of 70 sawtimber and pulpwood sized trees on the average simulated plot while 73 were observed in control plots. Simulated basal area was 19.3 m^2/ha at year 50 and 15.9 m^2/ha at year 100 as compared to 17.5 m^2/ha on control plots. The reduction of simulated basal area between years 50 and 100 was attributed to the death of several large trees.

The close approximation of simulated to actual stand parameters (species composition, tree number, basal area) for sites on land type 1 of the CWMA was accepted as satisfactory verification of FORCAT.

TABLE 6. Comparison of validation model output to regeneration observed in Sewanee study plots.

Species	Trees per 1/12 hectare plot							
	Under 1.37 m in height				Over 1.37 m in height			
	Simulated		Observed		Simulated		Observed	
	number	*percent*	*number*	*percent*	*number*	*percent*	*number*	*percent*
Oaks								
Northern red	65	8	161	6	0.2	0.5	0.4	1
Scarlet	22	3	13	1	1	3	—	—
Black	2	0.2	27	1	2	5	2	3
White	86	10	67	3	2	5	1	1
Chestnut	22	3	206	8	1	3	1	1
Blackjack	22	3	—	—	—	—	—	—
Post	23	3	—	—	—	—	—	—
Southern red	5	1	—	—	—	—	—	—
Group total[a]	247	29	474	18	6	16	5	6
Other overstory hardwoods								
Hickories	142	17	121	5	11	28	7	9
Yellow-poplar	14	2	640	25	4	10	9	12
Black cherry	27	3	31	1	1	2	—	—
White ash	104	12	143	5	4	10	3	4
Black walnut	2	0.2	5	0.2	—	—	0.4	1
Blackgum	73	9	58	2	4	10	14	18
Red maple	9	1	67	3	1	2	2	3
Sugar maple	39	5	72	3	2	5	5	7
Black locust	—	—	300	11	—	—	22	29
Group total	410	49	1,437	55	27	67	62	82
Understory species								
Sourwood	6	1	18	1	1	2	1	1
Dogwood	56	7	237	9	3	7	7	9
Sassafras	8	1	242	9	—	—	—	—
Am. holly	21	2	—	—	—	—	—	—
Am. chestnut	—	—	5	0.2	—	—	—	—
Winged elm	94	11	197	8	3	8	1	1
Group total	185	22	699	27	7	17	9	12
Total	842	100	2,610	100	40	100	76	100

[a] Group totals do not add due to rounding.

VALIDATION

PROCEDURES

Validation of FORCAT was conducted by a simulation of stand development on a different land type from that for which the model was developed. Model output was compared to a second data set collected on a 27.5 ha clearcut on the domain of the University of the South. This second study area is located on the escarpment of the Cumberland Plateau near Sewanee, Tennessee, and is described as land type 16 under Smalley's (1982) classification of forest sites. Soils are of the Grimsley, Jefferson, Ramsey, and Zenith series, have loamy textures, and are well drained (Smalley 1982). Aspect is predominantly to the north while slopes range from flat along benches to very steep between benches. Dominant species include chestnut oak (*Quercus prinus* L.), white oak, and northern red oak (*Q. rubra* L.) with common associates of hickories and yellow-poplar. Site index for yellow-poplar at 50 years averages 30.8 m.

Inventories of $\frac{1}{12}$ ha plots in the second study area were conducted prior to and 1 year after harvesting all stems over 20.3 cm dbh. The dbh, height, and species of each tree on the average study plot prior to harvest were included in the PLOTIN subroutine. FORCAT was run to simulate stand development for 100 years following diameter limit clearcutting (all stems over 20.3 cm dbh) on 100 independent plots.

RESULTS

Simulated regeneration during the first year after clearcutting is summarized and compared to field observations in Table 6. The average number of stems on simulated plots at year 1 (842) was considerably lower than the number observed in study plots (2,610). Even though the model underestimated the numbers of most species, the largest errors were for yellow-poplar, black locust (*Robinia pseudoacacia* L.), dogwood, sassafras, and chestnut oak.

With the exception of scarlet oak, errors of the magnitude found in validation were not observed during the verification of FORCAT. As was the case with the verification test, regeneration in the validation test consisted of a large number of sprouts of species that were present before clearcutting and relatively equal numbers of seedlings of all species. The SEEDPR subroutine functioned only to limit the invasion of heavy-seeded species without favoring the very light-seeded pioneer species such as black locust or yellow-poplar. In addition, an important source of seed for yellow-poplar is the seed bank in the soil and duff layer. Since this was not considered in SEEDPR, it may contribute to the underestimation of yellow-poplar regeneration. The SEEDPR subroutine was appropriate for the simulation of verification study plots where a seed source for pioneer species was essentially absent. However, the need for revising the simulation of seedling establishment to reflect the wide diversity of seed dispersal mechanisms between species is evident.

The underestimation of the numbers of dogwood, sassafras, and chestnut oak stems is partially due to a difference in harvesting methods used in the verification plots (CWMA) and the validation plots (Sewanee). The smallest tree cut at the Sewanee study area was 20.3 cm dbh. Since this diameter was larger than the one used during the validation test, the model harvested fewer stems. Therefore, only a small number of sprouts was included among plot regeneration. In contrast, all stems above 7.6 cm dbh were felled in CWMA study areas. By specifying this smaller diameter for simulated clearcutting, a much larger number of dogwood, sassafras, and chestnut oak stems became eligible to sprout. If a smaller diameter limit for clearcutting had been specified for the validation model, sprouts of all species may have been more abundant.

The occurrence of species in the validation test (Table 6), without considering relative numbers, was similar to that in the verification study. Black locust and American chestnut (*Castanea dentata* Marsh.), were present in field plots but absent from simulated plots in both tests. American chestnut was present in very small numbers in both CWMA and Sewanee plots and, therefore, was not included as model input. The absence of black locust is likely due to its habit of regenerating from rudimentary buds that remain dormant in the soil until the tree is injured or cut (Fowells 1965). Blackjack oak, post oak, southern red oak, and American holly (*Ilex opaca* Ait.) were included in simulated regeneration but were absent from observed plots. Since no trees of these species were present in the preharvest stand, all of the simulated regeneration was of seed origin. The numbers of seed-

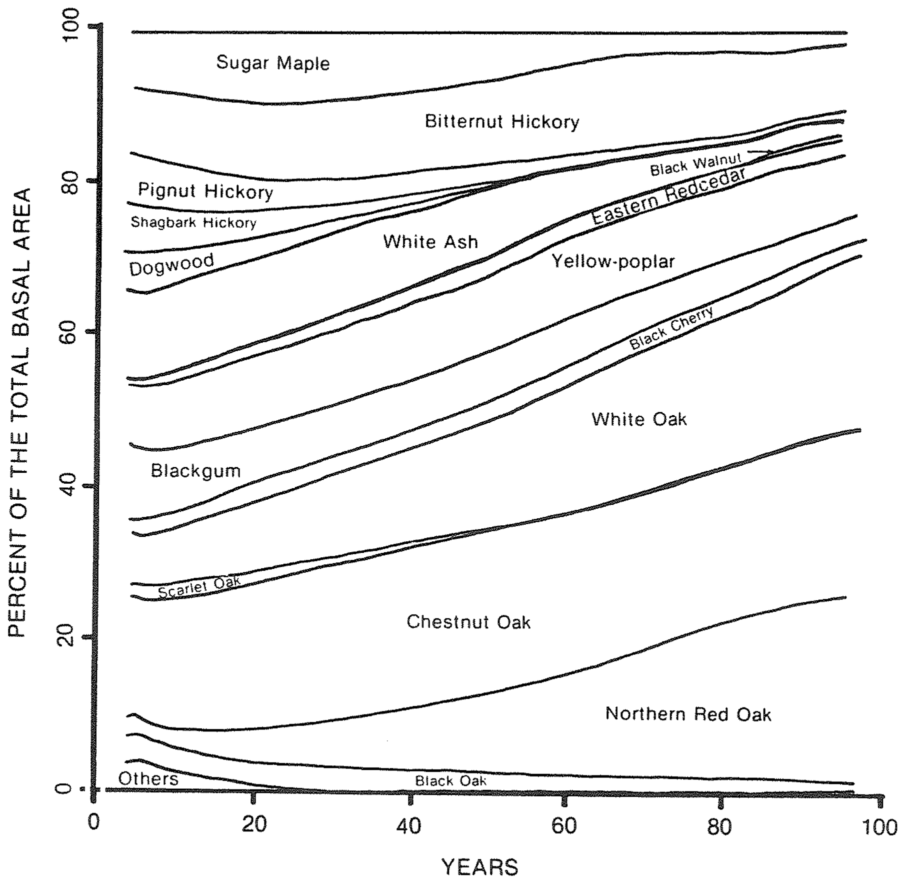

FIGURE 2. Simulated species composition for land type 16. The distance between any two curves at any point along the *X*-axis represents the percentage of the total plot basal area by that species at that particular stand age.

lings of these species were relatively small which prevented them from becoming major components of older simulated stands.

Although FORCAT underestimated the number of stems of pioneer species, this shortage did not appear to affect the prediction of species composition in the later years of the simulation period. Species composition for the average simulated plot is summarized in Figure 2 and compared to field data at selected stages of stand development in Table 7. Even though the values for model output at years 50 and 100 are based on plot basal area and the values for harvested trees are based on volume (International ¼ inch log rule), the expression of these as percentages should give an approximate comparison of species composition. In both simulated and observed field plots, stands were dominated by white oak, chestnut oak, and northern red oak with secondary occurrences of yellow-poplar, white ash (*Fraxinus americana* L.), sugar maple, and the hickories. Among the less common species, FORCAT tended to overestimate the abundance of eastern redcedar (*Juniperus virginiana* L.), sugar maple, black cherry (*Prunus serotina* Ehrh.), and blackgum and to underestimate the presence of black oak. The prediction of exact percentages during validation was considered to be less important than the prediction of general trends such as relative species abundance. In this

TABLE 7. Comparison of validation model output to preharvest stand data observed in Sewanee study plots.

Species	Total basa area		Total volume observed
	Simulated at year 50	Simulated at year 100	
	Percent		*Percent*
Oaks			
White	13.9	23.7	22.1
Chestnut	21.4	21.1	24.6
Northern red	10.7	25.0	18.6
Black	1.0	1.9	4.5
Group total	47.0	71.7	69.8
Other overstory species			
Hickories	14.9	9.1	11.8
Yellow-poplar	11.0	7.7	11.6
Black cherry	2.3	1.3	.2
White ash	8.8	2.4	3.9
Black walnut	.4	.4	.9
Blackgum	6.1	3.8	.7
Sugar maple	6.7	1.5	.8
Eastern redcedar	1.7	2.1	—
Group total	51.9	28.3	29.9
Understory species			
Dogwood	.5	—	—

sense, FORCAT provided an acceptable simulation of the species composition for mature forests on land type 16.

Across broad species categories (Tables 6 and 7), the model captured the tendency for oaks to increase at the expense of other hardwoods over the course of the simulation. A decrease in relative importance was most pronounced for pignut hickory, shagbark hickory (*Carya ovata* (Mill.) K. Koch), sugar maple, dogwood, and white ash (Fig. 2). The absence of black locust in the early regeneration of simulated stands largely accounts for discrepancies between measured and simulated stand parameters.

Other similarities between observed and simulated plots occurred with basal area and the number of merchantable trees (20 cm and over). The average basal area for preharvest plots on the Sewanee study area was 20.8 m^2/ha as compared to 19.8 for simulated plots at year 100. FORCAT predicted a total of 56.3 merchantable trees per ha at year 100 while an average of 60.8 per ha were harvested from Sewanee study plots. The total number of stems per simulated plot was not as accurate, however. Study plots had an average of 316 stems while the model simulated an average of only 120 at year 100. This difference was attributed to an underestimation of seedling numbers after the death of older trees near the end of the 100 year simulation.

CONCLUSIONS

The method used for validating the FORCAT model was fairly rigorous. Model validation was initiated by simulating stand dynamics for a mixed hardwood forest with more light-seeded species, broader species distribution, and higher site quality than found on the forest stand used for model development. However, FORCAT successfully predicted basal area, tree number, and species composition for mature stands on both sites. The underestimation of the number of seedlings of pioneer species emphasizes the difficulty in predicting short-term regeneration abundance and indicates the need for further model refinement. Nevertheless, FORCAT shows promise as a tool to project the future value of stands such as those where the model was developed and, to a lesser extent, those such as the validation area where light-seeded or pioneer species are abundant. In situations where the predictions of the quantity of early regeneration are not important, simulation can be initiated following clearcutting. The species and stem counts of regeneration observed in clearcut plots can be used as input to the PLOTIN subroutine to begin simulation with a young stand. In addition, FORCAT can simulate stand development after various cultural practices. The model can be readily altered to compare output to actual field data for varying rotation lengths, cutting limits, and/or fire history in young stands.

This study has demonstrated that gap models, which are widely accepted for their ability to model forest succession over periods of several centuries, also give accurate predictions of basal area, density, and species composition during simulations as short as 100 years. In this sense, FORCAT is a bridge between ecological and management-oriented predictive tools. Even though FORCAT underestimated the abundance of pioneer species, its ability to simulate regeneration was a considerable improvement over that of FORET. In addition, FORCAT retained the long-term predictive capabilities of its parent model. To further test the value of FORCAT as a predictive tool, the model should be tested in other areas prior to clearcutting. Descriptions of other preharvest stands should be included in the PLOTIN subroutine and model output compared to postharvest regeneration with strict validation procedures. Future work with the model should include further evaluation of stand regeneration dynamics, particularly seed availability, which will lead to refinements to make FORCAT even more accurate for simulation of early stand development.

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